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OBSERVATION AND ANALYSIS OF AN ICE HYDROMETEOR OF EXTRAORDINARY SIZE

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Summary. A fragment of a very large hydrometeor was analysed in the laboratory where standard thin-section techniques were used to reveal its structure. The ice fell at the time of a severe lightning stroke which occurred in Manchester on 2 April 1973, a day when heavy rainfall was recorded in the area. Inquiries have revealed the pattern of nearby aircraft movements at the time, and it is suggested that the lightning was triggered off by an aeroplane which flew into the storm. No definite conclusion as to the origin of the sample has been arrived at, except that it was composed of cloud water.

Introduction. The unusual meteorological conditions that occurred over the United Kingdom on Monday, 2 April 1973, caused widespread gales and heavy precipitation in many districts. The Coastguard station at Whitby, in Yorkshire, reported gusts of 110 mile/h, and shipping movements on the Mersey were suspended for part of the day owing to poor visibility. Gale-force winds and heavy rainfall were also recorded in southern districts. Manchester experienced a moderate snowfall in the morning, and this gave way to clearer skies in the afternoon. Shortly after sunset, cloud began to form and at 1900 GMT the cover was 3/8 cumulus with the base at 600 m.

At 1954 GMT a single flash of lightning occurred which extended over a very wide area of Manchester. This was noted by many people because of its severity, and because there were no further flashes. The Manchester Weather Centre recorded the lightning, which took a path at least 10 km long from Cheadle in the south to the city centre, and may have gone farther. A fall of hail in Wilmslow was observed at around the same time and there may well have been others. At the time of the stroke the author was walking along Burton Road, Manchester, near Withington Hospital, and, in his capacity as a lightning observer for the Electrical Research Association, he made a note of the time and nature of the flash as well as of the prevailing weather. The estimated interval between the flash and the thunder was two to three seconds, which suggested a lightning channel about 800 m away and, relative to the height of the cloudbase, almost directly overhead. No precipitation was

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observed at this stage. As the author returned a few minutes later by the same route, a large object struck the roadway about three metres to his left front, precisely at the junction of Burton Road with Bottesford Avenue (National Grid reference SJ 839922). This object fell fast enough to be shattered into many pieces on impact with the ground; only one fragment of any appreciable size could be found, the rest being scattered in tiny pieces over an area of many square metres. The time at which this object struck the ground was noted as 2003 GMT. On inspection, the fragments proved to be made of ice, and the large piece, when held up to the street light, showed rings of clear ice alternating with rings of bubbles trapped in the structure. Anxious to preserve this fragment so that it could be inspected in the laboratory, the author immediately ran home and was able to stow it in the freezing compartment of a domestic refrigerator in less than 10 minutes, with only minimal loss from melting. A light fall of sleet followed, lasting about 10 minutes. The air temperature was measured at this time, and was found to be 3°C; there was a just discernible breeze, which was too light for its direction to be fixed. The fragment was transferred to a cold room and a number of tests and experiments were performed on it in the hope that the results would throw some light on its probable origin.

Tests carried out on the fragment. As soon as possible after the ice was transferred to the laboratory, measurements of various kinds were made on the whole fragment, and photographs were taken to record its size and shape before the performance of any tests that would necessitate breaking the piece into smaller sections. The fragment weighed 612 g and was 14 cm in its longest dimension. The view seen in Plate I shows the layered structure of the whole piece. The centre of growth is missing, but it is evident from the disposition of the layers that the nucleus was somewhere in the region of the bottom left-hand corner as seen in the photograph, since the growth layer surfaces have an apparent centre at that point. The front of the sample in this photograph lies roughly in the plane of the apparent centre, and the outer layer, which is on the top and right sides, extends round to the back. The form of the layers shows that the original whole piece had roughly spherical symmetry, although distortion in this respect is introduced owing to the clear existence of a preferred direction of growth. It was decided to apply the techniques of structural analysis that are commonly used on hailstones. These involve the photography of thin sections of the ice sample in ordinary reflected or transmitted light, and also with the sections in various orientations between crossed polaroids. The former technique reveals the distribution of bubbles in the ice, and the latter shows the size and orientation of the crystallites; the crossed polaroid photographs are particularly effective if taken in colour, although black-and-white will often suffice. These photographs can then be used to extract information about the probable characteristics of the stages of growth in the ice specimen. Such methods have been used by many people and are described by List.[1]

In the process of preparing the sections it was possible to obtain samples of the melt water from successive layers of the fragment. The pH of this water was measured and all samples lay within the range 6·0 to 6·5, which is slightly basic relative to equilibrium with carbon dioxide at about 5·6 to 5·8 pH. The conductivity, σ, of the melt water was measured at 20°C and was found to

be 4·9 millisiemens per metre (mS/m), a value close to that measured for a sample of overnight rainwater (collected some time later in the same area) of 4 mS/m, supporting the view that the ice sample was composed of cloud water. By way of comparison, σ for tap water and laboratory-distilled water samples was found to be 20 mS/m and 0·3 mS/m respectively.

Preparation and photography of the thin sections. The sections were prepared and photographed in a cold room in which the temperature was maintained at −15°C. The ice sample was cut into six slices each about 0·5 mm thick which were then mounted on glass slides. The specifications of the six sections are given in Table I. The specimens were then placed in turn on a universal stage and photographed in black-and-white with transmitted light, and then in colour between crossed polaroid sheets.

TABLE I—SPECIFICATIONS OF SECTIONS

Section number	Shown in Plate	Plane	Location
1	II	Tangential	Parallel to section 2, 3 cm from the principal axis of growth
2	III, VI and VII	Radial	On the principal axis of growth
3	IV and VIII	Radial	Perpendicular to section 2; includes part of the polar surface layer at the smaller end
4	not shown	Tangential	Through the equatorial surface layer
5	V	Radial	Through the polar surface layer
6	VIII	Radial	Adjacent to section 3, showing a region intermediate between the centre and the surface

Note. A radial plane is any plane passing through the centre of a spheroid; a tangential plane is any plane that is not radial and is at some point tangential to one of the bubble-line surfaces. The polar region is at the end of the major axis and the equatorial region is at the end of the minor axis.

Interpretation of the photographs. Without making any assumptions about the origin of the ice fragment, the application of hailstone analysis techniques would appear to be the obvious approach in this case. Browning[2] presents a summary of the considerations involved in such work.

The fragment was found to have 51 layers of clear ice separated by thinner layers of trapped air bubbles. These features are clearly seen on the two large sections, 1 and 2, shown in Plates II and III respectively. The remains of the closest ring of bubbles to the centre can just be seen in Plate VII at the edge of the section before the first clear partial ring. The major and minor axes are taken to be those two directions, perpendicular to each other, in which the growth rates appear to be respectively greatest and least. A preferred direction of growth is indicated by the greater thickness of the rings of clear ice in the direction of the longer axis. The ratio of the semi-axes was 0·62 and this ratio is preserved in each growth layer of transparent ice. In the nomenclature adopted here, the centre is at the lower left of the bubble photograph of Plate II, the equatorial region is at the top left, and the polar region is at the bottom right. This terminology will be used throughout to identify the parts referred to. Diameters of the bubbles range from 0·1 to 0·5 mm, with a predominance at 0·2 mm. Of particular interest are the elongated bubbles

(indicative of growth near 0°C) in the rings near the growth centre of section 2 (Plate VII) which are up to 2 mm in length, and those in the surface layer (Plate VI) which are as much as 1·2 cm long. In Plate VII, a greater density of elongated bubbles in the direction of preferred growth is seen. This trend is reversed at the surface layer, where a much higher density occurs at the equator than at the pole. This can be seen most easily by comparison of sections 5 (Plate V) and 2 (Plate VI) and is also discernible in Plate III. In all the intermediate growth rings the density of bubbles is greater in the direction of preferred growth than in the equatorial direction, whilst the mean bubble diameter tends to be smaller, so that the amount of trapped gas remains roughly the same throughout the layer. There are at least three possible explanations for the mechanism of bubble trapping. In the first it is considered that the bubble rings are formed when the growing surface, with its temperature below some critical value, encounters a high density of supercooled droplets which freeze individually, and from the outside inwards. The dissolved gas which comes out of solution is then trapped within the ice. In this case the individual droplets should form many small crystals which will appear in layers (on the crossed-polaroid photographs) that coincide with the bubble layers (see Browning *et alii*[3]). Another possible explanation is that the growth is increased when the surface encounters a region of high liquid water content to such an extent that the rate of growth exceeds the rate at which bubbles can form and escape, and so they become trapped; however, the accreting drops are not frozen singly but are spread out over the surface forming single large crystals. This will occur at surface temperatures above some critical value, which for the 1-mm water drops impacting and freezing on single crystals studied by Hallett[4] was −5°C. Brownscombe and Hallett[5] found that new crystal orientations were adopted if the air temperature fell below a critical value, which was −5°C for 1-mm drops and −15°C for droplets of 20-μm radius. The third explanation suggested by Carte[6] is that the formation of a line of bubbles depletes the dissolved gas content of the water, and so subsequent growth is necessarily bubble-free until a new and adequate supply of dissolved gas becomes available. Carte studied this mechanism in the laboratory using films of water frozen between glass plates.

In order to test Carte's findings and also to determine the manner in which lines of bubbles are deposited in a growing ice sample, a number of ice cubes were grown in a refrigerator at various temperatures. Plate IX shows a thin section of a cube grown with its base maintained at −6°C. It is easily seen that air bubbles have formed in regularly spaced lines separated by clear ice. The bubbles first appear at random points in the ice structure, and become elongated; it is interesting to note that they terminate in fairly regular lines as the ice grows into the liquid, with a region of clear ice between each bubbly layer. We note that lines of bubbles have formed during the propagation of ice through a body of water in which the rate of growth is *not* affected by the rate at which water is supplied to the growing surface—as it would be in growth by accretion—since here the total body of water frozen is made available at the outset. However, it would seem that, in both types of growth, bubble lines can be interpreted as contours marking the extent of the ice surface at any one time, and can also show the direction of growth in that the elongated bubbles terminate in regular lines on the side of the layer facing that direction. These findings support the view that the hydrometeor studied here grew in the

direction of increasing bubble-ring radii, as a hailstone would, rather than in the other direction which could be the case were it an artefact of some sort. The bubble distribution seen in the ice cube sample (Plate IX) lends support to the gas-depletion process envisaged by Carte. Whether or not the same effect may take place in an ice body growing by accretion is not clear, but it seems probable that, in order for it to occur, very thick layers of unfrozen water would have to build up on the growing surface.

In order to investigate the nature of ice growth in a container, several toy balloons were filled with water, suspended in a refrigerator and allowed to freeze. The frozen masses of water showed no tendency to produce bubbles in regular lines, but rather they were distributed in a random fashion throughout the ice sample. In addition, the direction of freezing was seen—by inspection at various times—to be from the outside inwards, leaving an unfrozen pocket of water within the frozen shell. As this pocket froze the stresses set up caused the ice shell to crack; the resultant ice structure bore no resemblance to the fragment studied here, suggesting again that the ice was not produced by freezing in a container.

The thickness of the layers in the direction of preferred growth varied from as little as 0·5 mm up to 8 mm (not counting the 20-mm thick surface layer), with 2 mm being typical. Inspection of the photographs revealed that there was a portion of a line of bubbles remaining near the growth centre. A few of these are just discernible in Plate VII. The minor axis of this line of bubbles was found to be somewhat less than 8 mm so that the original nucleus at the centre of growth was certainly no larger than this in diameter.

Examination of the photographs showed crystals ranging in size from a few millimetres to several centimetres, with the long axes of growth in the radial direction; there were no regions of small crystals coincident with the bubble rings. A few smaller crystals were apparent, distributed throughout the sample, but with a preponderance in the surface layer. The lower portion of Plate VIII shows many small crystals in the ice structure. These appeared spontaneously during melting of the specimen between glass plates to reduce its thickness from 0·5 mm to 0·2 mm. Care must be taken to identify such an event during handling of the ice samples if spurious conclusions are to be avoided.

Aircraft movement in the area. McDonald[7] has reviewed many occurrences of falls of ice, some of which may be due to detachment from aircraft de-icing gear. In order to gain as much information as possible on the origin of the piece of ice studied here, extensive inquiries were made at Ringway, Manchester's airport for civil aircraft, which is about 8 km south of the place where the ice fell. A landing approach path from Barton Moss in the north-west takes aircraft on a course east-south-east to Stockport in the east, where the turn is made to approach the runway from the north-east. This flight path passes 1 km to the north of the junction of Burton Road with Bottesford Avenue (McLaren, Ward and Partners[8]). Two aircraft were known to have followed this approach path at around this time, one landing at 2001 GMT (a Danair Comet) and the other at 2006 GMT (a Swissair flight). No reports of icing, abnormal radio interference, antenna damage or malfunction of any kind were made to Air Traffic Control from either of these aircraft or from any others. Specific inquiries were then made of the engineers' departments handling these two flights, and it transpired that the Comet landing at 2001 GMT had

been struck on the starboard side of the nose by lightning which discharged via the elevators, although this had not been reported at the time by the captain during the approach. The flight was then referred back to Air Traffic Control, and its precise location ascertained at 1954 GMT, the time of the lightning stroke. The plane was at that moment at 8000 ft, near Barton Moss, about 20 km north-west of Manchester Airport. It subsequently dropped to 5000, 3000, 2000 and 1500 ft and made a normal 3-degree approach.

In view of the proximity of this aircraft to the area in which this lightning stroke occurred, the fact that it was struck is not altogether surprising. Since there was only one stroke, and the time and the aircraft location is known, the probable extent of the flash should be extended to at least 20 km. The way in which aircraft and thunderstorms interact has been studied by several people, notably Byers and Braham,[9] Newman[10] and Vonnegut.[11] From considerations of the probability of an aircraft being struck by lightning, Vonnegut, drawing on Newman's data, tentatively suggests that the presence of an aircraft may increase the probability of a lightning stroke occurring. The circumstances of the lightning described here support this suggestion, since the aircraft may very well have been responsible for initiating the flash in a region of electrified cloud where the field intensity was insufficient to generate the discharge by more conventional means, which are assumed to require higher fields because of the small size of particles (of rain, snow or hail) involved. The absence of any subsequent lightning further indicates that the electrical development of the storm was insufficient to give rise to naturally initiated discharges.

Weather conditions in the area. The nearest upper-air sounding station to Manchester is about 40 km distant at Aughton, near Liverpool. The following ascent was recorded at 0000 GMT on Tuesday, 3 April: wind direction and speed at the surface and at 1·5 and 3·0 km altitude, 350° 7 kt, 330° 34 kt and 330° 41 kt respectively; air temperature 2·5°C at the surface, 0°C at 2·5 km and −31°C at 4·5 km; cloudbase 600 m. These wind-shear figures are comparable with those recorded at the time of the storm of 1 July 1968 near Cardiff in which giant hailstones fell, as described by Macklin *et alii*.[12] The 24-hour reports for 2 April 1973 show the following rainfall values in the vicinity: Southport 20 mm, Blackpool 25 mm, Morecambe 25 mm, Douglas 28 mm, Manchester Airport 18 mm; hail was recorded at Douglas and Anglesey. The Manchester 10-year averages for the months of March and April are 53 mm and 66 mm respectively and the annual rainfall is 888 mm. It is noted that the 24-hour rainfall figure constitutes one-third to one-half of the monthly average.

Comments on the origin of the ice hydrometeor. To make a definitive statement on this question is a very difficult task. The properties of the ice sample are in some ways very much like those of a hailstone. However, the size of the fragment suggests that the original may have weighed as much as 1·0 to 2·0 kg, which is large even compared to the Coffeyville hailstone which weighed 0·76 kg (Knight and Knight[13]). On the other hand, the nucleus of growth was less than 10 mm in diameter. If such a large growth of ice built up on an aircraft, it would need to be on something like a radio antenna or some other component of small size. The aerodynamic forces on such a body

would be enormous at normal flight speeds, even when making the slow landing approach, and it seems unlikely that there would be no damage to the component. Further, specific inquiries showed that no damage had been reported by the aircraft on the flight path in question, or indeed by any others in the air at the same time, other than the lightning strike to the Danair Comet at 1954 GMT, which landed before the ice fell. Again, the shape of an ice growth starting from a small nucleus on an aircraft at normal flight speed would be expected to exhibit far greater elongation in the airstream direction than is displayed by this body, where the degree of growth in the directions parallel and perpendicular to the major axis is the same within a factor of 2; such a mode of growth is consistent with all known characteristics of hailstones and it is hard to visualize how it could have occurred on an aircraft. Furthermore, if such a heavy growth accumulated at one location on an aircraft, one would expect heavy icing over the rest of the forward-facing surfaces, and, as stated previously, such icing was not reported on any aircraft in the air at the time.

The ice sample displays a puzzling collection of features. Whilst it is clearly composed of cloud water, there is no conclusive evidence enabling one to decide precisely how it grew, except that laboratory tests suggest that this sample did not grow in a container. In some respects it is very much like a hailstone, whilst in others it is not. Equally, the possibility that it was formed by icing on an aircraft is not borne out by the flight records. The author welcomes correspondence on this open question.

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VERTICAL WIND SHEAR IN THE LOWEST 600 METRES AT SHOEBURYNESS

By M. J. DUTTON

Summary. An analysis of vertical wind shear in the lowest 600 metres at Shoeburyness using 5 years of day-time pilot-balloon soundings has shown that the largest day-time shears in the layer between the surface and a height of 50 metres occur most frequently in conditions of general free convection with moderate to strong surface winds off the land, and are probably mainly attributable to the natural gustiness of the wind in these lowest layers. Overall, 21 per cent of shears exceeded 80 m s^{-1} km^{-1} (4·74 kt per 100 ft) and 1·7 per cent of shears exceeded 160 m s^{-1} km^{-1} (9·47 kt per 100 ft); 1·2 per cent exceeded 10 kt per 100 ft.

A limited comparison of Shoeburyness with Larkhill (an inland site) for the surface–200-m layer showed no significant difference between the derived shear-frequency distribution for the two sites.

Introduction. Vertical wind shear is obviously an important factor in the safety of landing and take-off operations, and it is generally recognized that the final 60 metres or so of descent of a landing aircraft are the most critical. In particular, for a large aircraft on approach to touchdown, the effects of a rapidly decreasing head-wind component (that is to say rapid loss of airspeed) during the last 60 metres of descent could prove disastrous.

The International Civil Aviation Organization (ICAO)[1] has made several recommendations concerning wind-shear conditions during landing and take-off phases. Among these recommendations was an interim shear criterion (5th Air Navigation Conference of ICAO, 1967), namely that vertical wind shear, when reported quantitatively, should be expressed according to the following classification:

Category	Magnitude of shear		
	m/s per 30 m	*m/s per km*	*kt per 100 ft*
Light	0–2·5	0–83	0–4·9
Moderate	2·5–4·5	83–150	4·9–8·9
Strong	4·5–6·0	150–200	8·9–11·7
Severe	>6·0	>200	>11·7

This classification was not officially accepted because it cannot apply universally to all types of aircraft.

In 1973 a question about the frequency of occurrence of strong vertical wind shear in the lowest layers at a coastal site arose out of the requirement for a third London Airport at Maplin: how did the frequency of occurrence compare with that at a typical inland site? This report presents the results of an analysis of five years (1968–72) of day-time pilot-balloon ascents at Shoeburyness to produce a climatology of vertical wind shear across various layers (ranging in thickness from 40 m to 400 m) from the surface up to 600 m. It should be stressed from the outset, however, that 'vertical wind shear' in the context of this paper does not refer to the true vertical shear of the mean wind but to an *apparent* vertical wind shear, the difference between a balloon-sensed wind averaged over a layer and a surface wind averaged at a fixed point (or another balloon-sensed wind) divided by the thickness of the layer across which the wind change is measured. This point should be borne in mind in the interpretation of the results.

The report incorporates the results of a similar analysis of five years' (1968–72) pilot-balloon ascents at Larkhill, an inland site, for comparison with the Shoeburyness results. Direct comparison of the results is limited to the surface–200-m layer since the rates of balloon ascent used at Larkhill were normally too large to allow finer resolutions in the vertical. The comparison is also limited to morning ascents, as the Larkhill soundings took place at or near 0900 (all times in this paper are expressed in Greenwich Mean Time and are nominal times, the actual ascents having taken place within ±30 minutes of the exact hour).

The observations

Shoeburyness. All the pilot-balloon soundings (for which the requisite information was available) at Shoeburyness from 1968 to 1972 inclusive (5 years) provide the basic observations. The balloon was tracked by single theodolite until a sufficiently accurate radar fix was obtained, normally at two minutes from balloon-release time; the radar slant range was not accurately measurable when less than 500 metres. In consequence the great majority of ascents include theodolite fixes (elevation and azimuth) at ½ minute and 1 minute with a radar fix (elevation, azimuth, and height derived from elevation and range) at 2 minutes. The balloon heights at ½ minute and 1 minute were usually subjectively interpolated, the radar-allocated heights being used at and after 2 minutes.

Only the first two minutes of each sounding were required for this investigation, so that the ½-minute, 1-minute and 2-minute balloon fixes (elevation, azimuth, height) together with a surface (10-m) wind, measured close to the balloon-release site, provided all the necessary data. The surface wind is an average of 10 spot readings, 5 taken over a period of 1 minute immediately before balloon release, and a further 5 over a period of 1 minute immediately following termination of the ascent (typically 10 to 15 minutes after balloon-release time).

At Shoeburyness all the ascents are restricted to day-time. Soundings are made at various times but normally at 0800/0900 on weekdays (Monday to Friday); in addition a sounding is usually made at 1200/1300. If no firing exercises have been planned no ascent is made at 1200/1300. The exercises are usually planned a few days in advance. Occasionally, in adverse weather conditions such as bad visibility, strong winds or the presence of a marked

temperature inversion, the exercise may be cancelled and no sounding be required, but this happens very infrequently; any resulting bias in the sample of soundings made at 1200/1300 is only very slight. The soundings made at 0800/0900 can be considered meteorologically as being relatively unbiased.

Table I shows the distribution of ascent times; 48·7 per cent of all ascents took place at 0800 or 0900 and 37·6 per cent took place at 1200 or 1300.

TABLE I—TIME DISTRIBUTION OF ASCENTS (SHOEBURYNESS)

Time (GMT) ± 30 min	5	6	7	8	9	10	11	12	13	14	15	16	17	18
No. of ascents	5	23	37	729	158	58	73	550	136	23	20	7	3	1

Total number of ascents = 1823.

The balloon rates of ascent used at Shoeburyness varied widely but the great majority were in the broad range of 100 to 300 metres per minute.

Larkhill. Again, pilot-balloon soundings at Larkhill from 1968 to 1972 provide the basic observations, but there were some major differences in the details of the standard ascent procedure. The ascents at Larkhill did not include a ½-minute balloon fix; in addition all the soundings took place between 0700 and 1000 with 94 per cent of them at 0900 (Table II) and the ascent rates used were generally greater than those at Shoeburyness.

TABLE II—TIME DISTRIBUTION OF ASCENTS (LARKHILL)

Time (GMT) ± 30 min	7	8	9	10
No. of ascents	9	5	714	31

Total number of ascents = 759.

Analysis of observations. The derived layer-meaned winds were imputed to the layer mid-points in the normal way; for each Shoeburyness ascent four winds were available whereas each Larkhill sounding yielded three winds. The vector wind shear, **S**, across a layer was defined as the magnitude of the vector wind change across the layer divided by the layer thickness:

$$\mathbf{S} = \frac{\mathbf{u}\,(h_2) - \mathbf{u}\,(h_1)}{h_2 - h_1},$$

where $\mathbf{u}\,(h_1)$ and $\mathbf{u}\,(h_2)$ are the winds at heights h_1 and h_2 ($h_2 > h_1$) and $S = \pm|\mathbf{S}|$.

S was defined as positive if $|\mathbf{u}(h_2)| \geqslant |\mathbf{u}(h_1)|$ (wind speed increasing or constant with increasing height) and negative otherwise. With this system (PIBAL) of determining the vertical wind shear, the derived shear, S, is not a measure of the true vertical shear of the mean wind but an *apparent* vertical wind shear, the difference between

(a) a balloon-sensed wind averaged over a layer, and
(b) either a surface wind averaged at a fixed point or another balloon-sensed wind;

divided by the thickness of the layer across which the wind change is measured. This is an important point and its implications will be discussed later.

To simplify the analysis a degree of layer standardization was introduced. At Shoeburyness each actual layer was assigned one of the nominal layers 10–50 m, 10–100 m, 10–200 m, 10–400 m, 50–100 m, 50–200 m, 50–400 m, 100–200 m, 100–400 m and 200–400 m. For Larkhill ascents only three nominal layers were used, namely 10–200 m, 10–600 m and 200–600 m.

The Shoeburyness analysis included categorization in terms of time of ascent (0500–1000) and (1100–1800), season (the four main seasons) and surface wind direction ('sea' winds 040–219 degrees and 'land' winds 220–039 degrees). The Larkhill shears were categorized by season only.

Mean wind profiles for the Shoeburyness ascents were also computed; these were categorized by time of ascent (as above), season (summer half-year and winter half-year) and surface wind direction (300–039° open country with few towns; 040–149° open sea—long fetch; 150–239° sea/estuary—shorter fetch; 240–299° including built-up areas). For each category mean profiles of $\bar{u}/\bar{u}_{10}$, the ratio of mean wind speed to 10-m mean wind speed, and wind-direction veer, defined as zero at the surface, were computed. To eliminate some of the very large wind-direction variations with height which often occur in calm or light-wind conditions, the wind profiles were constructed using only ascents for which the surface wind speed exceeded 4 kt.

Errors of measurement. The error in the shear derived from single-theodolite/pilot-balloon measurements is dependent on the errors in elevation, azimuth, allocated height (these determine the error in the mean wind imputed to the layer mid-point) and, for shears across layers with base at the surface, the surface wind. Estimates can be made of the likely root-mean-square (r.m.s.) errors in the measured variables involved in the computation of shear magnitude, the two most important errors, particularly for shears in the lowest 50 metres, being elevation (especially at low elevation) and allocated balloon height. As has already been pointed out, the ½-min heights are allocated, not by assuming a constant rate of ascent, but by subjective interpolation using radar fixes at and after 2 minutes, so the level of r.m.s. error in allocated balloon height is obviously reduced appreciably from that applicable to ascents in which tracking by single theodolite alone is used and a constant rate of ascent is assumed for the balloon. The 2-min radar fix is sufficiently accurate to provide a good measure of the mean ascent rate through the lowest 400 m or so (the 2-min height in fact varied widely in the range 250–600 m); the mean effect (smoothed over the lowest 400 m) of vertical air motions is therefore effectively implicit in the derived ½-min and 1-min balloon heights. What we cannot know about, however, is the sub-structure of the vertical motion within this surface–400-m layer, and we can expect errors in allocated heights at ½ minute and 1 minute (particularly the former) to be largest when the variations with height (within this layer) of the ascent rates are large. Typical conditions in which the variations might be appreciable are those in which a relatively shallow convection layer near the surface is capped by a stable layer.

It so happens in fact that, in the lowest layer, the computed shear, which is the difference between the measured winds at two levels divided by the thickness of the intervening layer, is not as sensitive to the size of the ascent-rate error as might at first appear to be the case, since the errors in both the numerator and denominator of the division are always in the same sense, that is to say an overestimate of the balloon height (and therefore of the layer thickness) produces an overestimate of the wind difference, and vice versa.

Typically, in conditions of moderate to strong shear, the r.m.s. error in the computed shear magnitude across the lowest layer at a balloon elevation of 10° and ½-minute allocated balloon height of 100 m is about 30 to 40 m s^{-1} km^{-1}

(1·8 to 2·4 kt per 100 ft). An overall value applicable to all moderate/strong wind occasions would be about 25 to 30 m s^{-1} km^{-1}.

Discussion of results

Shoeburyness

(a) *Lowest layer—surface to 50 m.* The level of error in the computed shear magnitudes is quite high for this layer and the derived shear-frequency distributions must be treated with due caution, particularly in any detailed examination of the frequencies of the largest shears. Despite this, some interesting conclusions about the variation with different categories (time, season, surface wind direction) of the shear-frequency distributions can be drawn.

(1) *Frequencies of shear magnitudes* $\geqslant$ 80 *m* s^{-1} *km*$^{-1}$ (Table III). The figures show that significantly more of these shears occur with 'land' winds (220–039°) than with 'sea' winds except in winter; in the winter/1100–1800 category the difference is strikingly reversed.

For each of the wind direction/time categories except 'land'/1100–1800 the maximum frequencies are in winter. For the 'land'/1100–1800 category the minimum frequency is in winter, with maximum in spring and summer, both the spring and summer frequencies of these moderate to severe shears being approximately double the winter frequency.

The frequencies for 'sea' winds, for each of the seasons, show no significant variation with time category, although the all-year figures show a marginally greater frequency for the 0500–1000 period. For 'land' winds, however, the larger frequencies in the 1100–1800 period in spring and summer are significant, as is the decreased frequency in the same time category in winter.

(2) *Frequencies of shear magnitudes* $\geqslant$ *160 m* s^{-1} *km*$^{-1}$ (Table IV). The limited number (total of 29 in 5 years) of these large shears makes it difficult to assess the significance of any of the observed variations in frequencies of occurrence from category to category but it is encouraging that most of the variations are broadly similar to those found for the shears discussed above.

The figures in Table IV show that these large shears occurred more frequently in 'land' winds except in the winter/0500–1000 category; in fact 23 out of 29 of these shears occurred in 'land' winds. For 'sea' winds, in the 0500–1000 period the frequencies are about 1 per cent for each of the seasons, and again, as for the moderate to severe shears, the 1100–1800 frequencies are greater (for all seasons) than the 0500–1000 frequencies, with the minimum 1100–1800 frequencies in winter. Over the year as a whole, shear magnitudes exceeded 160 m s^{-1} km^{-1} on 1·7 per cent of occasions, 10 kt per 100 ft on 1·2 per cent of occasions, and 6 m/s per 30 m or 200 m/s per km on 0·5 per cent of occasions.

Closer study of the 17 largest measured shears ($S \geqslant 180$ m s^{-1} km^{-1}) showed that most occurred at 1200 and all but one occurred when the surface wind direction was in the range 220 to 320 degrees. The lowest surface wind speed associated with these largest shears is 6 m/s, and one possibility which springs to mind initially is that the large shears may simply be associated with occasions when the r.m.s. errors were likely to be large. (Strong winds, implying low initial elevation angles, produce the largest errors). But simple chi-square tests on the relationship between the incidence of large shears and moderate to

TABLE III—SHOEBURYNESS, SURFACE TO 50 METRES, PERCENTAGE FREQUENCIES OF WIND SHEAR EQUAL TO OR EXCEEDING 80 m s^{-1} km^{-1} (4·74 kt PER 100 ft)

Surface wind direction	Time	Winter	Spring	Summer	Autumn	Year
040–219° ('sea')	0500–1000	33·8	9·5	5·1	12·8	16·4
	1100–1800	29·1	10·1	8·2	8·2	13·5
220–039° ('land')	0500–1000	35·0	22·6	18·6	21·2	23·7
	1100–1800	17·8	33·8	34·6	27·8	28·1
All	0500–1000	34·5	18·2	13·8	18·4	21·0
	1100–1800	22·8	23·4	19·6	19·5	21·1
All	All (0500–1800)	28·9	20·1	16·4	18·7	21·0

TABLE IV—SHOEBURYNESS, SURFACE TO 50 METRES, PERCENTAGE FREQUENCIES OF WIND SHEAR EQUAL TO OR EXCEEDING 160 m s^{-1} km^{-1} (9·47 kt PER 100 ft)

Surface wind direction	Time	Winter	Spring	Summer	Autumn	Year
040–219° ('sea')	0500–1000	5·0(5)	0·0	0·0	0·0	1·5(5)
	1100–1800	0·0	0·0	0·9(1)	0·0	0·3(1)
220–039° ('land')	0500–1000	0·8(1)	0·6(1)	1·4(2)	1·2(2)	1·0(6)
	1100–1800	2·0(2)	5·0(5)	3·7(3)	7·0(7)	4·5(17)
All	0500–1000	2·8(6)	0·4(1)	0·8(2)	0·8(2)	1·1(11)
	1100–1800	1·2(2)	2·9(5)	2·2(4)	4·1(7)	2·4(18)
All	All (0500–1800)	1·9(8)	1·3(6)	1·4(6)	2·0(9)	1·7(29)

Figures in brackets represent numbers of cases.

strong surface winds ($u_{10} \geqslant 5$ m/s) from various directions indicate that the relative incidence of large shears for winds in the 120-degree direction range 210–329° is significantly higher than for winds in the ranges 330–089° and 090–209°. This is so, both for the 17 shears with $S \geqslant 180$ m s^{-1} km^{-1} and for the 29 shears with $S \geqslant 160$ m s^{-1} km^{-1}, and it does not support the view that the largest measured shears occur because of large errors due to strong winds.

A study of the synoptic situations associated with the incidence of large shears revealed that, of the 17 largest shears, 13 occurred in generally free-convective conditions with moderate to strong surface winds (implying near-neutral stability in the lowest layers), and usually with showers reported in the vicinity. One way in which this bias of large measured shears towards moderate/strong wind conditions may be explained involves the natural gustiness of the wind near the surface. It has already been pointed out that the measured surface–50-m shear is effectively the difference between the balloon-sensed wind (averaged over the layer from the surface to about 100 m and over 30 seconds following the motion of the air) and the surface wind measured near the balloon release point. From the results of various studies of the relationship between Lagrangian ('following the motion') and Eulerian ('fixed-point') wind statistics, summarized for example by Pasquill,[2] we can estimate that, typically, with moderate/strong winds and near-neutrally stable conditions in the lowest 100 m, a balloon-sensed (Lagrangian) 30-second wind is equivalent to something like a 5-second fixed-point (Eulerian) wind. In other words, the wind with which the balloon is carried along in the first 30 seconds of flight is approximately equivalent to the layer wind averaged (at the release point) over the 5 seconds immediately following the balloon release time. By assuming

that in moderate/strong winds there is no significant bias towards releasing the balloon in lulls (or gusts) it is therefore possible to carry out a simple analysis to determine the expected distribution of large measured shears produced by the natural variability of the 5-second fixed-point winds (assuming also that the measured shears are normally distributed about the mean shear). Then, from estimates, for near-neutral steady-state boundary-layer conditions in moderate/strong winds, of the mean surface–50-m shear and its variance, made up of the contributions from the natural variability of the 5-second winds and that from the errors of measurement, we can estimate an expected probability of occurrence of any magnitude of measured shear for a given surface wind speed. So, given a large number of ascents we can compute an expected distribution of large measured shears from a knowledge of the surface wind speed and direction frequencies.

The mean shear can be obtained from the logarithmic law for neutral stability:

$$\frac{\bar{u}_h}{\bar{u}_{10}} = \frac{\log (h/z_0)}{\log (10/z_0)}, \quad (\text{for } h \gg z_0),$$

using appropriate roughness lengths* (z_0) for different wind directions; estimates of the variance contribution from the variability of the 5-second winds can be inferred from the work of Durst[3] and many others. Estimates of the r.m.s. measurement errors have already been discussed. In applying the logarithmic law to the Shoeburyness wind-speed profiles, roughness lengths ranging from 0·5 cm for 'sea' winds to 20 cm for westerly 'land' winds have been used. The different roughness lengths used for different directions obviously also imply different 5-second wind variances since larger roughness lengths imply greater wind variability near the surface.

For each wind speed/direction category a computed mean shear and associated expected standard deviation imply an expected normal distribution of measured shear. By summing the individual distributions from all the wind speed/direction categories, an overall expected shear distribution for the large shears ($\geqslant$ 100 m s^{-1} km^{-1} say) can be obtained.

The results of this analysis are shown in Table V. For 'sea' winds the observed frequency of shears $\geqslant$ 120 m s^{-1} km^{-1} is almost four times as great as that predicted. For 'land' winds the distributions are in much better agreement although the difference between them is significant almost solely because of the large difference between the numbers of the largest shears ($S \geqslant$ 180 m s^{-1} km^{-1}).

TABLE V—SHOEBURYNESS, SURFACE TO 50 METRES, COMPARISON OF PREDICTED AND OBSERVED WIND SHEAR FREQUENCY DISTRIBUTIONS

	Shear (m s^{-1} km^{-1})								
	<60	60–80	80–100	100–120	120–140	140–160	160–180	⩾180	Totals
Expected (sea)	555	75	35·7	13·6	4·2	1·2	0·3	—	685
Observed (sea)	485	98	49	32	11	4	5	1	685
Expected (land)	613	144	100	61	33·3	17·9	8	6·7	984
Observed (land)	580	154	107	61	43	16	7	16	984

* The roughness length is effectively a measure of the roughness of the underlying surface.

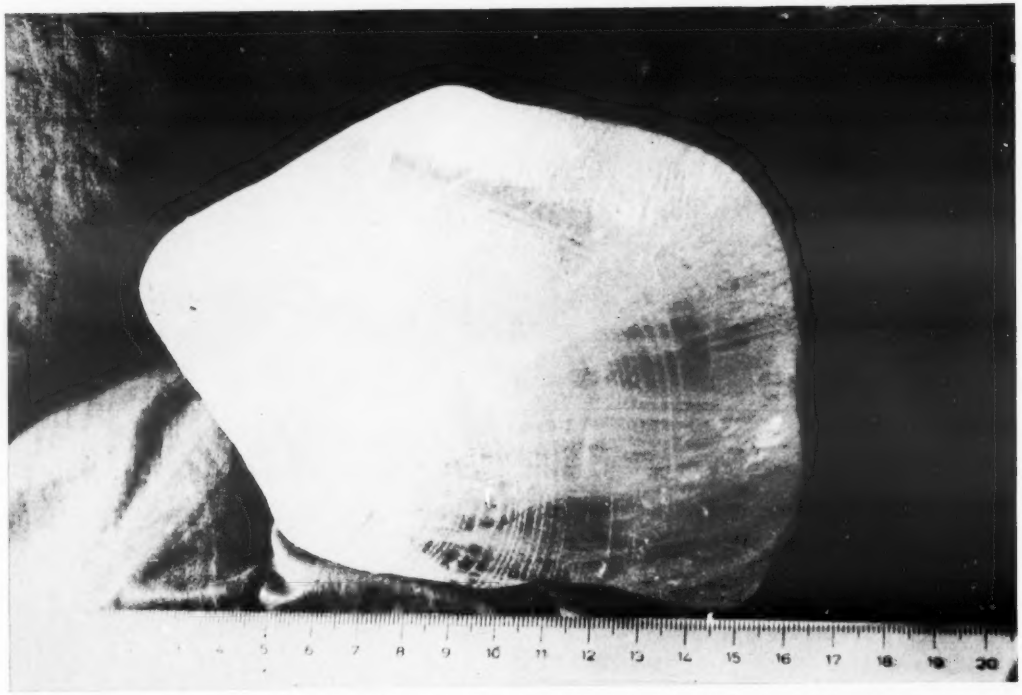

PLATE I—A VIEW OF THE FRAGMENT BEFORE SECTIONING, SHOWING THE LAYERED STRUCTURE

The scale is in centimetres.

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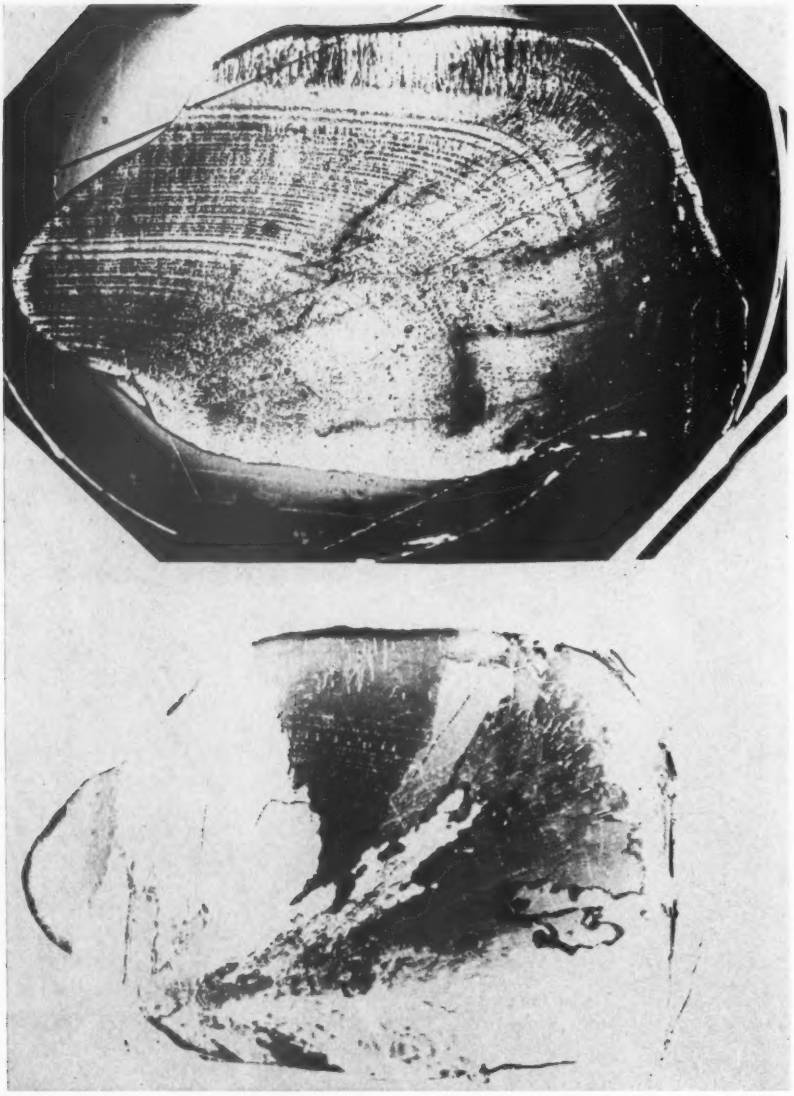

PLATE II—A PHOTOGRAPH OF SECTION I

The upper view shows the layer and bubble structure in transmitted light; the lower view shows the crystal fabric between crossed polaroids. The longest dimension of the sample is 13 cm.

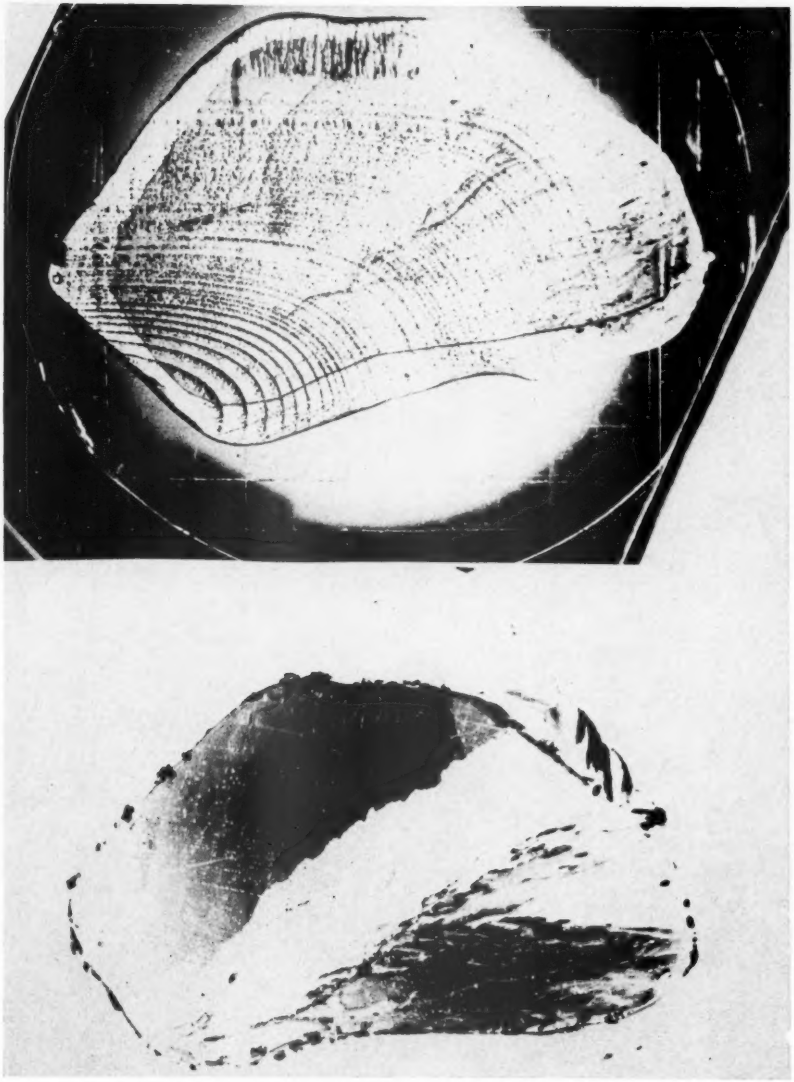

PLATE III—A PHOTOGRAPH OF SECTION 2
Comments are as for Plate II. Longest dimension is 12 cm.

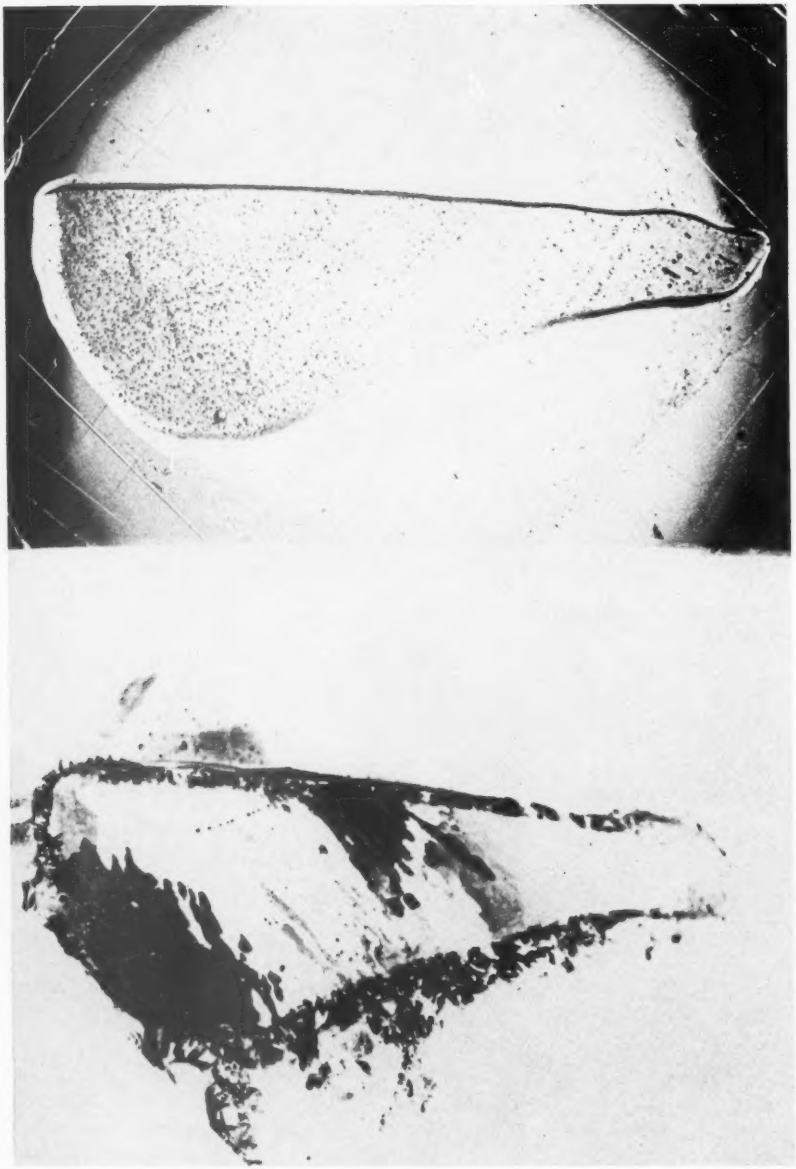

PLATE IV—A PHOTOGRAPH OF SECTION 3
Comments are as for Plate II. Longest dimension is 11·5 cm.

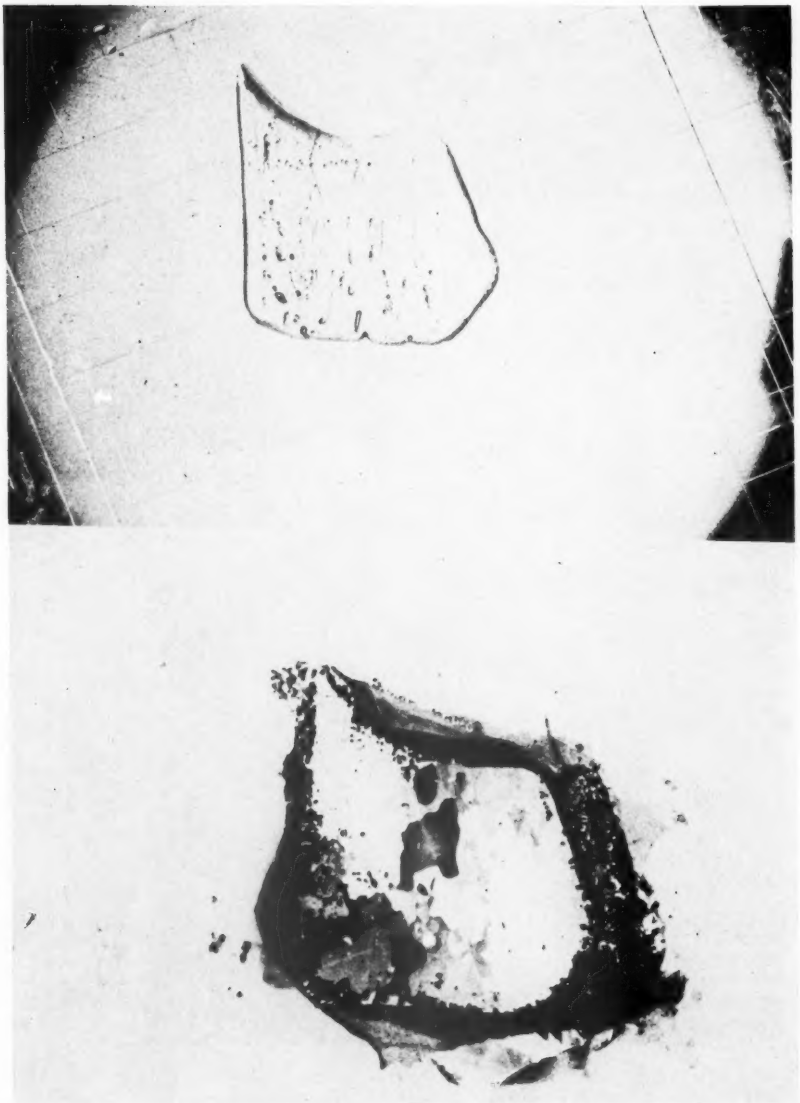

PLATE V—A PHOTOGRAPH OF SECTION 5
Comments are as for Plate II. Longest dimension is 5 cm.

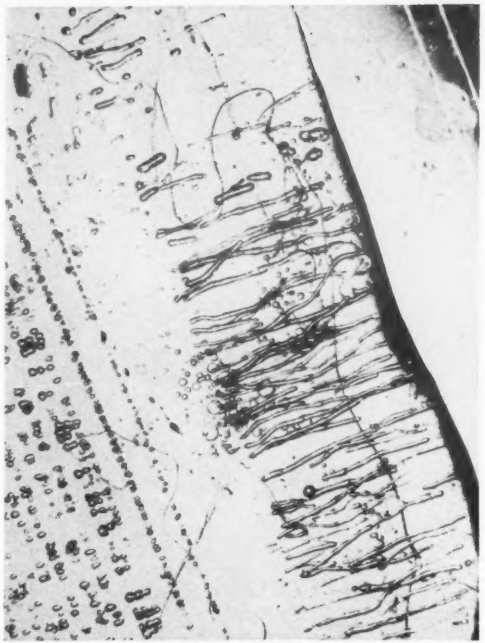

PLATE VI—SECTION 2: CLOSE-UP OF THE EQUATORIAL SURFACE LAYER

Distance from the line of small non-migrating bubbles to the surface is about 2 cm and the surface layer of migrating bubbles is 1·2 cm thick.

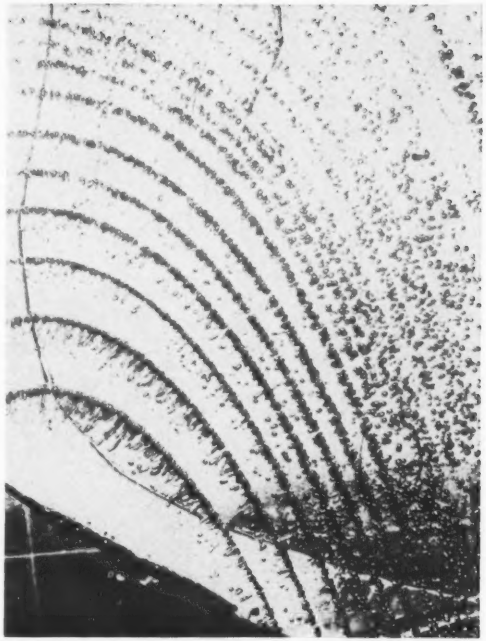

PLATE VII—SECTION 2: CLOSE-UP OF THE GROWTH RINGS NEAR THE CENTRE

The long axis of the photograph represents 5 cm.

PLATE VIII—SECTIONS 3 (UPPER) and 6 (LOWER) AT TWO STAGES OF RECRYSTALLIZATION INDUCED IN A THIN LAYER BY MELTING BETWEEN TWO GLASS PLATES
Section 6 is 0·2 mm thick at this stage and its longest dimension is 2·7 cm.

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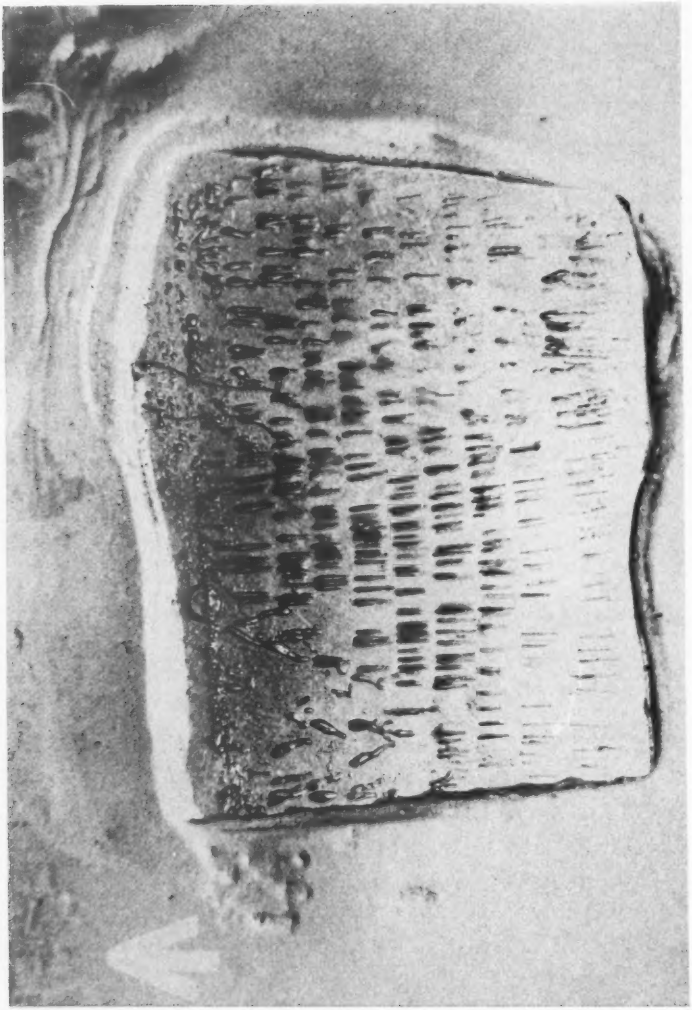

PLATE IX—A THIN SECTION OF AN ICE CUBE GROWN WITH ITS BASE MAINTAINED AT −6°C

The lines of trapped bubbles are clearly seen, the elongation being in the direction of growth, as indicated by the arrow.

The main shortcomings of the application of this method of predicting the distribution of large measured shears in moderate/strong winds are:

(1) Non steady-state cases, where there may be large changes of wind direction and/or speed during the period of the ascent, are not allowed for. Exclusion of such cases reduces the predicted occurrence of large shears.

(2) The necessary assumption that there is no significant bias towards releasing the balloon in lulls is only strictly valid in the strongest wind conditions. This assumption obviously therefore produces overestimates of the occurrence rates of the larger shears.

However, the analysis does appear to predict quite well the frequency distribution of shears in excess of 60 m s^{-1} km^{-1} with winds off the land and probably explains why the majority of the largest shears occur in 'land' winds. For 'sea' winds the analysis significantly underestimates the frequency of shears in excess of 100 m s^{-1} km^{-1}; this discrepancy may be due to a combination of two main factors:

(1) The roughness length applicable to moderate/strong 'sea' winds can vary considerably depending on the exact nature of the sea surface; it may often exceed the assumed overall value of 0·5 cm, particularly in strong winds with a very disturbed sea surface. Use of the higher values of roughness length for strong winds would increase the expected number of the largest shears.

(2) Modification of the mean profile and turbulence intensity may sometimes be significant during passage of the air over the short distance from the coastline to the sampling point, particularly when the land is much warmer than the sea.

(b) *Surface to 100 m.* Across this layer there were no measured shear magnitudes in excess of 160 m s^{-1} km^{-1}; the largest shear was 137 m s^{-1} km^{-1} (8·1 kt per 100 ft). Table VI contains the percentage frequencies of $S \geqslant 60$ m s^{-1} km^{-1} (3·55 kt per 100 ft); this threshold was chosen in preference to the 80 m s^{-1} km^{-1} used for the surface–50-m shears because there were so few shears exceeding that magnitude in this layer (19 in all, representing 2·6 per cent of all shears in this layer).

The seasonal variations are quite well defined for these shears, with the maxima usually in winter and minima in summer.

TABLE VI—SHOEBURYNESS, SURFACE TO 100 METRES, PERCENTAGE FREQUENCIES OF WIND SHEAR EQUAL TO OR EXCEEDING 60 m s^{-1} km^{-1} (3·55 kt PER 100 ft)

Surface wind direction	Time	Winter	Spring	Summer	Autumn	Year
040–219° ('sea')	0500–1000	19·5(9)	12·9(5)	5·0(1)	9·5(4)	12·9(19)
	1100–1800	6·5(3)	4·2(2)	2·0(1)	0·0	3·4(6)
220–039° ('land')	0500–1000	12·7(6)	6·4(4)	4·5(3)	10·9(6)	8·2(19)
	1100–1800	11·3(5)	8·2(4)	8·0(4)	8·5(4)	8·9(17)
All	0500–1000	16·1(15)	9·0(9)	4·7(4)	10·3(10)	10·1(38)
	1100–1800	18·9(8)	6·2(6)	5·0(5)	4·9(4)	6·3(23)
All	All (0500–1800)	12·6(23)	7·0(15)	4·8(9)	7·9(14)	8·2(61)

Figures in brackets represent actual numbers of cases.

(c) *All other nominal layers.* Table VII and Table VIII (a)–(c) summarize the main results for all nominal layers including those already discussed in detail above. Table VII lists the largest measured shears for each of the nominal layers; Table VIII lists the percentage frequencies of $S<0$ (negative shears), $0 \leqslant S < 80$ and $S \geqslant 80$ m s^{-1} km^{-1} for three of the most relevant categories. In the higher nominal layers, particularly in the 100–200-m layer, the relatively high frequencies of negative shears are interesting. In the 100–200-m layer 36·9 per cent of all shears were negative; for summer this figure rises to 50 per cent for all directions, and 65 per cent when only 'land' winds were considered.

(d) *Mean wind profiles.* The computed mean wind profiles (wind speed as a proportion of surface wind speed, and veer from surface wind direction) are shown in Figures 1(a)–(d); they include only those ascents in which the surface wind exceeded 4 kt, for the reasons given in the 'Analysis of observations' section. Note that the season and wind-direction categories differ from those used in the analysis of vertical wind shear. (In the figures, N is the total number of cases sampled in the lowest levels, up to at least 200 m, and N' is the number sampled at the level where the profile terminates.)

Larkhill/Shoeburyness comparison—surface to 200 m. For reasons already explained, direct comparison between Shoeburyness and Larkhill vertical wind-shear frequency distributions is unfortunately limited to only one nominal layer, the surface–200 m layer, and to one time category, 0500–1000 (0700–1000 for Larkhill).

Table IX compares the distributions for this layer at Shoeburyness (0500–1000) and Larkhill (0700–1000), taking into account all surface wind directions at both sites. Although the figures show that there were consistently slightly more of the largest shears ($S \geqslant 40$ m s^{-1} km^{-1}) at Shoeburyness, none of the differences are statistically significant. In comparing the figures it should be borne in mind that the bulk of the Shoeburyness 0500–1000 soundings used in the analysis took place at 0800 (72 per cent), with some at 0500–0700 (6·5 per cent), whereas 94 per cent of the Larkhill 0700–1000 soundings took place at 0900, with only 1·8 per cent before this time at 0700–0800. On the simple basis therefore that the frequency of occurrence of the strongest shears *across this layer* (surface–200-m) is greatest in the early hours of the morning and decreases with increasing solar elevation, the frequency of these shears would be expected to be slightly greater in the Shoeburyness sample where the ascent times were an hour or so earlier on average.

Résumé and concluding remarks. This study of vertical wind shear in the lowest layers at Shoeburyness and Larkhill is a limited study in several senses:

(a) The measured shear is an *apparent* wind shear and not the true vertical shear of mean wind.
(b) Only day-time shears are analysed.
(c) Errors in computed shears across the surface–50-m layer at Shoeburyness are rather large.
(d) The Shoeburyness/Larkhill comparison is restricted to the surface–200-m layer and to morning ascents only.

However, the object of the study was to extract as much information as possible about the climatology of the vertical wind shear in the lowest layers at

TABLE VII—LARGEST SHEARS IN VARIOUS NOMINAL LAYERS

Nominal layer	Layer thickness	S_{max}	Root-mean-square error estimate
metres		*m s⁻¹ km⁻¹*	
10–50	40	278	35
10–100	90	137	15
10–200	190	90	10
10–400	390	59	10
50–100	50	148	25
50–200	150	110	15
50–400	350	56	10
100–200	100	58	15
100–400	300	56	10
200–400	200	72	10

TABLE VIII—PERCENTAGE FREQUENCIES OF SHEAR MAGNITUDES IN VARIOUS NOMINAL LAYERS (SHOEBURYNESS)

(a) All year, all directions, all times 0500–1800 GMT

Nominal layer *m*	$S < 0$	$0 \leqslant S < 80$ m s^{-1} km^{-1}	$S \geqslant 80$ m s^{-1} km^{-1}	Total number of cases
	Percentage frequencies			
10–50	8·1	70·9	21·0	1669
10–100	5·5	91·8	2·6	746
10–200	5·4	94·4	0·2	1311
10–400	4·3	95·7	0·0	1715
50–100	13·2	84·6	2·2	595
50–200	20·3	79·3	0·4	1231
50–400	14·7	85·3	0·0	1519
100–200	36·9	63·1	0·0	228
100–400	24·2	75·8	0·0	634
200–400	27·0	73·0	0·0	1160

(b) All year, directions 040–219°, all times 0500–1800 GMT

Nominal layer layer *m*	$S < 0$	$0 \leqslant S < 80$ m s^{-1} km^{-1}	$S \geqslant 80$ m s^{-1} km^{-1}	Total number of cases
	Percentage frequencies			
10–50	12·8	72·3	14·9	685
10–100	9·8	88·7	1·5	326
10–200	7·6	92·4	0·0	499
10–400	8·3	91·7	0·0	693
50–100	10·1	87·6	2·3	267
50–200	16·5	83·5	0·0	475
50–400	14·6	85·4	0·0	618
100–200	37·0	63·0	0·0	81
100–400	24·3	75·7	0·0	277
200–400	33·3	66·7	0·0	439

(c) All year, directions 220–039°, all times 0500–1800 GMT

Nominal layer *m*	$S < 0$	$0 \leqslant S < 80$ m s^{-1} km^{-1}	$S \geqslant 80$ m s^{-1} km^{-1}	Total number of cases
	Percentage frequencies			
10–50	4·7	69·9	25·4	984
10–100	2·2	94·5	3·3	420
10–200	4·0	95·8	0·2	812
10–400	1·6	98·4	0·0	1022
50–100	15·5	82·4	2·1	328
50–200	22·7	76·7	0·6	756
50–400	14·7	85·3	0·0	901
100–200	36·8	63·2	0·0	147
100–400	24·1	75·9	0·0	357
200–400	23·1	76·9	0·0	721

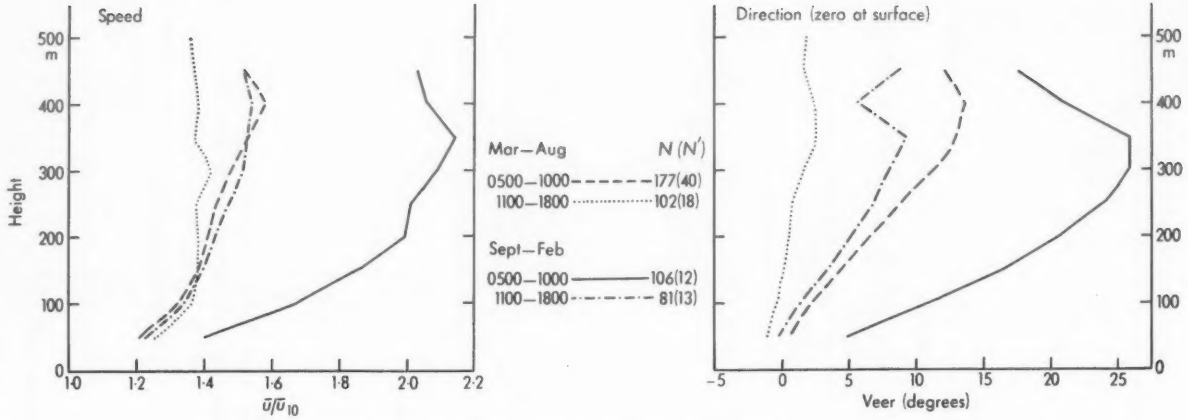

FIGURE 1—SHOEBURYNESS MEAN WIND PROFILES (1968–72)

(a) Surface wind direction 300–039 degrees. (N is the total number of cases sampled in the lowest levels up to 200 m and N' is the number sampled at the level where the profile terminated.)

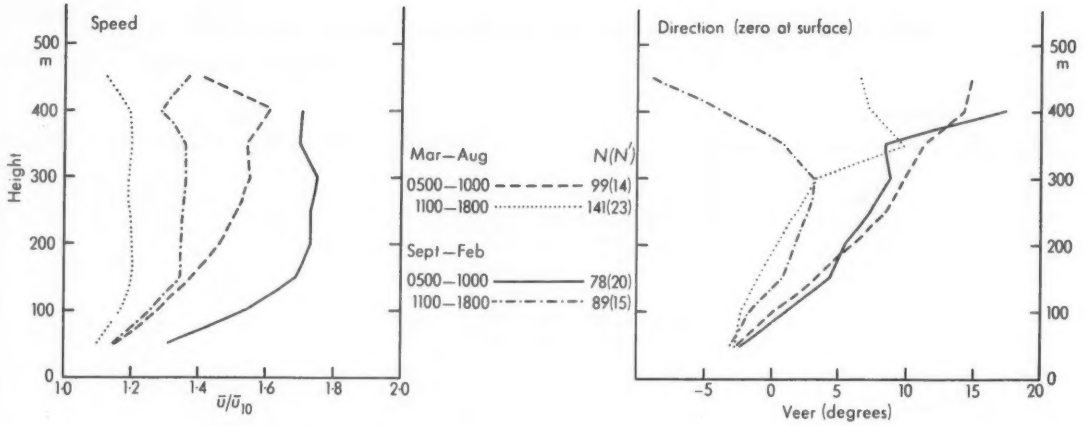

FIGURE 1—*continued*

(b) Surface wind direction 040–149 degrees. (For explanation of N and N' see notes under Figure 1 (a).)

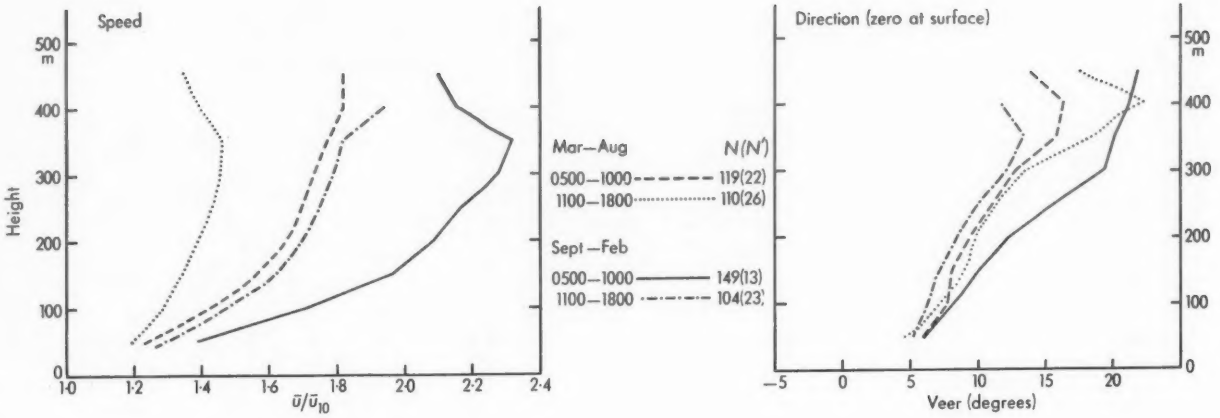

FIGURE 1—*continued*

(c) Surface wind direction 150–239 degrees. (For explanation of N and N' see notes under Figure 1 (a).)

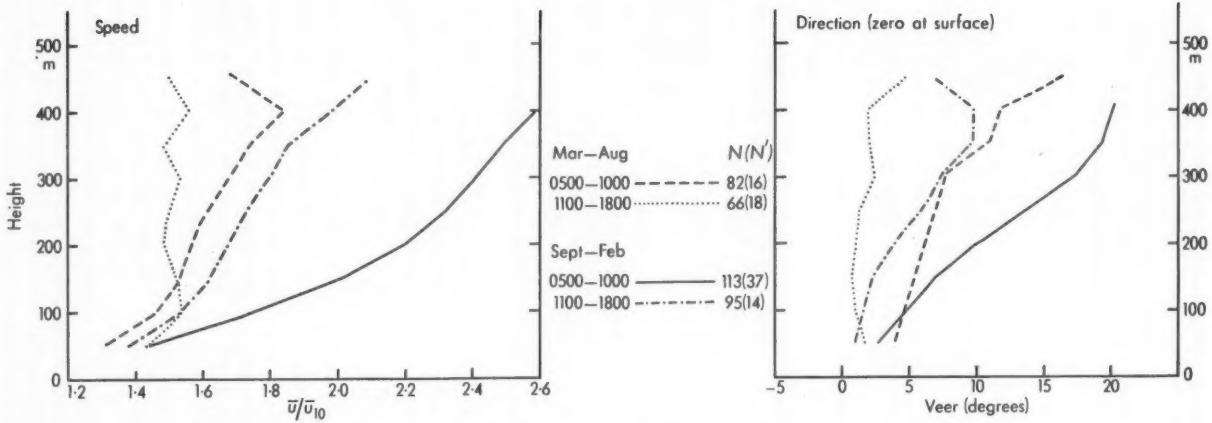

FIGURE 1—*continued*

(d) Surface wind direction 240–299 degrees. (For explanation of N and N' see notes under Figure 1 (a).)

TABLE IX—COMPARISON OF SHEARS IN THE SURFACE–200-m LAYER AT LARKHILL (0700–1000 GMT) AND SHOEBURYNESS (0500–1000 GMT) (ALL SURFACE WIND DIRECTIONS INCLUDED)

Season	Site	$S < 20$ m s^{-1} km^{-1}	$20 \leqslant S < 40$ m s^{-1} km^{-1}	$S \geqslant 40$ m s^{-1} km^{-1}	Total number of cases
		Percentage frequencies			
(all year)	Larkhill	44·4	39·3	16·3	759
	Shoeburyness	40·4	38·5	20·2	749
Winter	Larkhill	15·9	48·4	35·7	182
	Shoeburyness	14·7	44·7	40·6	170
Spring	Larkhill	54·8	34·1	11·1	208
	Shoeburyness	49·5	36·1	14·4	205
Summer	Larkhill	70·4	26·5	3·1	196
	Shoeburyness	70·5	23·8	5·7	193
Autumn	Larkhill	32·4	50·3	17·3	173
	Shoeburyness	26·6	50·5	22·8	184

Shoeburyness and Larkhill from existing and readily available records of pilot-balloon soundings; although the limitations obviously necessitate some caution in the interpretation of the results, this object has been achieved.

Shoeburyness—surface–50-m layer. The largest day-time shears occurred most frequently in generally free-convective conditions with moderate to strong surface winds from directions in the range 210–330 degrees; 23 of the 29 largest shears (with $S \geqslant 160$ m s^{-1} km^{-1}) occurred with winds off the land. In winds originating over the sea the largest shears occurred almost exclusively in winter in the 0500–1000 period.

Overall, 21 per cent of shears exceeded 80 m s^{-1} km^{-1} (4·74 kt per 100 ft) and 1·7 per cent exceeded 160 m s^{-1} km^{-1} (9·47 kt per 100 ft); 1·2 per cent exceeded 10 kt per 100 ft.

For 'land' winds the frequency distribution of shears $\geqslant 80$ m s^{-1} km^{-1} is in quite good agreement with that expected (except for $S \geqslant 180$ m s^{-1} km^{-1}), a normal intensity of turbulence in near-neutral conditions being assumed; for 'sea' winds, however, the predicted frequency of shears $\geqslant 120$ m s^{-1} km^{-1} is only about a quarter of the observed frequency.

Shoeburyness—other layers. With winds off the land the maximum frequency of the biggest shears occurred in winter with the minimum in summer; with winds off the sea the maximum also occurred in winter but the minimum in autumn.

Shear magnitudes exceeded 80 m s^{-1} km^{-1} on 2·6 per cent of occasions across the surface–100-m layer, on 0·2 per cent of occasions across the surface–200-m layer, and on 2·2 per cent of occasions across the 50–100-m layer.

Larkhill/Shoeburyness comparison. The figures for the surface–200-m layer in the morning period show that there were consistently, in all four seasons, more of the larger shears (with $S \geqslant 40$ m s^{-1} km^{-1}) at Shoeburyness, although none of the differences are statistically significant. However, it is obvious that the nature of the wind-shear distribution for the surface–50-m layer is quite different from that for the surface–200-m layer and so it is not possible to draw firm conclusions about the relative incidence of large day-time shears in the lowest layer at Shoeburyness and Larkhill from the relative incidence in the surface–200-m layer.

General comparison of inland and coastal sites. The Shoeburyness results provide a basis for some qualitative speculation about the comparability of coastal and inland sites from the point of view of the incidence of excessive day-time vertical wind shear in the lowest 50 m (as measured by pilot-balloon soundings). Most of the largest shears occurred in generally free-convective conditions with moderate to strong surface winds off the land, and appear to be mostly attributable to the natural gustiness of the wind in these lowest layers. Over the year as a whole an inland site may be expected to have more excessive day-time shears than the coastal site on the simple basis that the generally greater roughness lengths (considering all directions) associated with an inland site imply larger mean shears and turbulence intensities. If the terrain at the inland site is similar to that to the west and north of Shoeburyness, then the overall frequency of large day-time shears would be expected to approximate to that for 'land' winds at Shoeburyness, assuming that the inland site has a similar synoptic experience. This conclusion probably does not apply to the winter months since Shoeburyness results show that most of the largest shears in the surface–50-m layer in winter are associated with winds off the sea.

The limitation of the observations to the period 0500–1800 prevents useful extension of the speculation to night-time shears.

Acknowledgements. Thanks are due to the Meteorological Office staffs at Shoeburyness and Larkhill for their much appreciated efforts in the collection of the data used in this report.

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FIFTH LONG ASHTON SYMPOSIUM ON ENVIRONMENTAL EFFECTS ON CROP PHYSIOLOGY, UNIVERSITY OF BRISTOL, 13–16 APRIL 1975

By MARJORY G. ROY

This international symposium was held at the University of Bristol to mark the retirement of Professor J. P. Hudson from Long Ashton Research Station. It attracted over 150 participants, many of whom were from overseas, and the residential nature of the arrangements at one of the Halls of Residence of the University encouraged some lively discussions, apart from those during the official sessions.

In his inaugural lecture on the evening of 13 April Professor Hudson posed the question whether enough was known about plant responses to weather and climate for action to be taken to even out the weather-induced year-to-year variations in yields of many crops (notably fruit crops) by breeding or appropriate cultivation techniques. It was suggested that even if reliable seasonal or longer-period forecasts were available the agricultural industry could not utilize them at present to improve yields.

The five sessions of the symposium were on 'Weather and Crop Productivity', 'Physiological Processes–Assimilate Production', 'Physiological Processes—Respiration and Translocation', 'Critical Stages of Plant Development', and 'Modelling the Synthesis of Results'. To agricultural meteorologists the papers presented in sessions I, IV and V were most closely related to problems which they might have to tackle, but the more technical papers in sessions II and III emphasized the problems of measuring plant response to the environment and the interpretation of the results obtained. The use of physical and biological models to simulate plant and crop response to weather and climate has highlighted the gaps in experimental and theoretical knowledge of the interactions between plants and the weather and there was some heated discussion of the usefulness of the model-building techniques in such a situation. It was generally agreed that although models could for instance provide realistic estimates of the build-up of dry matter in vegetative material, they did not as yet cope satisfactorily with phenological change in the crop (initiation and development of flowering, filling of storage organs such as grains etc.). These are of great significance for most agricultural and horticultural crops where the harvested yield (grains, roots, fruit etc.) is only a part of the total biomass.

Although some useful relations between yield and weather have been obtained using simple correlation techniques, it seems likely that further progress depends on greater understanding of the interactions of crops and weather at a more fundamental level. This symposium showed how much further basic research has to go before it becomes feasible to predict for any crop (or indeed variety of a single crop) the yield to be expected with a given set of weather conditions during the growing season. In the context of yield, the problem of dealing with plant diseases was mentioned and it was suggested that in many cases these were now the limiting factors in crop production.

The symposium was most efficiently organized by Drs J. J. Landsberg and C. V. Cutting and their team from Long Ashton, and the excellent chairing of the different sessions kept the discussion both lively and relevant.

REVIEWS

Review of urban climatology 1968–1973, WMO *Technical Note* No. 134, by T. R. Oke. 275 mm × 210 mm, pp. xviii + 132, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1974. Price: Sw.Fr.20.

Dr T. R. Oke, acting as a rapporteur on urban climatology for the WMO Commission for Special Applications of Meteorology and Climatology, has produced this review which documents the developments in the study of urban

climate since the Brussels Symposium on Urban Climates and Building Climatology in 1968, the proceedings of which were published by WMO as *Technical Notes* 108 and 109. The author's approach to this task is a sound one, since he arranges his review to deal separately with the basic physical processes which are of importance in the urban environment. In each of the three sections devoted to the balances of radiation, water and energy, he describes in essence the fundamental theoretical and observational problems which exist and discusses critically the attempts which have been made in recent years to tackle these problems.

The following section entitled 'Climatological Effects' is a collation of the results of observations of conventional climatological elements in and around urban areas. An indication of the development of interest in urban climatology is provided by a count of over 20 urban areas which were the subjects of published 'heat island' studies during 1972 alone.

The problems of airflow in and over cities provide a continuing challenge, and engineers concerned with the design of tall wind-sensitive structures are vocal in their demands for advice on wind profiles and characteristics of turbulence in the first few hundred metres above ground. The lack of uniformity of surface roughness in urban areas is obviously the main difficulty here, and estimates of roughness length for different cities vary widely, often because of unsatisfactory allowance for zero-plane displacement. Recent experimental attempts to study the wind field using balloons are reviewed. These have contributed to our knowledge of conditions in light or moderate winds, but profiles and turbulence in strong winds are obviously of most practical concern for the structural engineer.

The final section of the review is devoted to discussion of advances in numerical modelling of urban atmospheric conditions, which can be traced back to Gold's (1956) simple model which developed a sea-breeze type of circulation from initially calm conditions due to low-level temperature differences. At the end of this section, the outstanding problems in modelling are summarized and the desirable characteristics of a boundary-layer model for the study of the urban atmosphere are set out.

The extensive bibliography updates admirably the work of Chandler* and provides a useful starting-point for a newcomer to the field.

J. S. HOPKINS

Atmospheric diffusion—the dispersion of windborne material from industrial and other sources, by F. Pasquill. 225 mm × 150 mm, pp. xi + 429, *illus.*, Ellis Horwood Ltd, Coll House, Westgate, Chichester, Sussex, 1974. Price: £16.

The first edition of Dr Pasquill's book *Atmospheric diffusion* requires no introduction to those seriously interested in or working on the topic. This second edition, although following the same general pattern as the first, is fully justified

* CHANDLER, T. J.; Selected bibliography on urban climate. Geneva, World Meteorological Organization, 1970.

in that the original material has been brought up to date and expanded as necessary and a greater emphasis has been placed on the practical applications of the concepts and techniques presented, something which will be appreciated by everyone actively involved in problems of effluent dispersal.

A brief, but well-balanced, introductory chapter is followed by three chapters dealing respectively with the relevant properties of atmospheric turbulence, theoretical representations of diffusion and observational aspects of the topic. Chapters 2 and 3 provide the reader with considerable insight into time and distance scales in relation to horizontal and vertical diffusion, the effects of stability and wind shear, and the range of applicability to gradient transfer, similarity- and statistical-theory treatments of diffusion, to name but the more important aspects discussed. Close attention is given to physical reality throughout and Chapter 4 complements this with a detailed discussion of the more important experimental studies of the basic features of atmospheric diffusion, providing the reader with an appreciation of the limitations of the theoretical descriptions of diffusion. The difficulties of obtaining the relevant data, particularly in the vertical, for validation of the theory are highlighted.

From the point of view of the person involved in the computation of the distribution of pollution emitted from real sources, the final two chapters (5 and 6) are the most important. Chapter 5 deals with various aspects of diffusion from real sources and includes sections on plume rise, pollutant removal mechanisms, effects of topography and buildings, pollution from urban areas (multiple sources) and long-range transport. Chapter 6 is intended to be self-contained and is aimed at the person who has to apply the techniques and theory (discussed in the previous chapters) to obtain estimates of the current or future distribution of a pollutant. On the whole the chapter meets its objective and gives the practitioner an excellent appreciation of the concepts involved and their practical implications. Considerable stress, and rightly so, is laid on the importance of departures from the idealized conditions assumed in the theoretical representations and on the relative sensitivity of the estimates to the assumptions and values of the parameters involved (for instance the correct specification of the plume spread is more important that the Gaussian assumption). Overall the material in this book is very well presented and clearly set out with apparently very few errors—I noticed just the one. Obscurities are rare, although the definition of stability at the beginning of Chapter 6 could prove confusing to some readers.

The person involved in making pollution estimates may be disappointed by the lack of positive recommendations in certain sections (for example on how to cope with specific topographical features and on the R & D areas which are likely to be the most fruitful in producing better estimating systems) and some sections (for example on urban pollution and on practical systems of calculating dispersion) show some imbalance. In these two sections perhaps not enough consideration is given to work carried out in the U.S.A. and elsewhere in comparison with that in the United Kingdom. However, relative to the quality of the book as a whole, these are mere quibbles. In conclusion one must unreservedly recommend this book to all who are involved in the theoretical or practical aspects of atmospheric diffusion.

A. W. C. KEDDIE

NOTES AND NEWS

Retirement of Mr L. S. Clarkson

Mr L. S. Clarkson studied Physical Chemistry at Liverpool University and was awarded a B.Sc. degree with first class honours in 1936 and an M.Sc. in 1937. He joined the Meteorological Office in 1940 and during the early part of the Second World War he had several postings in the United Kingdom. In 1943 he joined the Royal Air Force Volunteer Reserve (Meterorological Branch) and served as a Flight Lieutenant at Headquarters No. 93 Group, in West Africa and at No. 4 Group. He was demobilized in August 1946 but continued to serve at No. 4 Group in the grade of Senior Scientific Officer. In 1947 he was posted to No. 21 Group and in 1951 to the Flying Training, Army and Ministry of Supply Branch of the Meteorological Office at the Headquarters in London. On promotion to Principal Scientific Officer in January 1954 he became Chief Meteorological Officer at Headquarters Far Eastern Air Force (Singapore) and he stayed there until mid 1957 when he was posted to London Airport (Heathrow) where he stayed for six years. In 1965 he again went overseas—this time to Cyprus. After his return to the United Kingdom late in 1966 he served at Uxbridge, the Instruments and Observations Branch (later known as the Operational Instrumentation Branch) and the Observational Requirements and Practices Branch. He was promoted there to Senior Principal Scientific Officer early in 1973 and became Assistant Director. He continued to serve in this capacity until his retirement in July 1975.

Mr Clarkson has had a varied career in a variety of places; throughout he has applied a single-minded purpose and shown a thorough appproach to all his work. Work prepared by him or under his supervision has the stamp of painstaking, methodical and comprehensive preparation and he has consistently reached his decisions after careful consideration of the problems. When his mind was made up he would adhere to the view and defend his deductions and policy logically and strongly. In his latter years of work at Headquarters he was Chairman of some HQ Working Groups dealing with observational problems both of a conventional kind and those involving the use of weather radars. By his systematic and thorough approach to the several problems he has contributed significantly to the success of these Working Groups and has guided their deliberations well.

Mr and Mrs Clarkson will continue to reside near Chertsey. Their many friends and colleagues in the Meteorological Office will, I am sure, wish them both a long and happy retirement and hope that they both keep in good health to enjoy their sailing and other activities.

N. BRADBURY

Daily synoptic weather maps from the 1780s

In the *Meteorological Magazine* for February 1975 Mr. J. A. Kington* gave an account of the work being undertaken at the Climatic Research Unit of the University of East Anglia on the construction of daily synoptic charts for the

* KINGTON, J. A.; Daily synoptic weather maps from the 1780s: a research project of synoptic climatology. *Met Mag, London*, 104, 1975, pp. 33–52.

latter part of the eighteenth century, commencing with the year 1781. The first four years, 1781 to 1784, have now been microfilmed and a copy, on 35-millimetre film, is available for inspection in the National Meteorological Library, Bracknell. It is hoped that eventually at least 10 consecutive years will be completed and made available for public use in this manner.

Transliteration of Cyrillic alphabets

The Meteorological Office has decided that henceforward any transliteration from Cyrillic alphabets will be made according to the joint system of the British Permanent Committee on Geographical Names (PCGN) and the U.S. Board on Geographic Names (BGN); this will apply to the cataloguing work of the National Meteorological Library at Headquarters, Bracknell and to references and bibliographies contained in Meteorological Office publications. The languages involved include Russian, Bulgarian, Ukrainian, White Russian and Serbian. This decision, which came into force on 1 June 1975, implies a reversion to the practice obtaining before 1959 at which time the Meteorological Office adopted the ISO/R9 system in order to be in line with a recommendation made by the World Meteorological Organization; however, the hoped-for international unanimity in the use of ISO/R9 never came about, and the large number of diacritical signs employed in this system make it unsuitable for computerized catalogues.

The BGN/PCGN system is described in the following publication: *Romanization Guide*, U.S. Board on Geographic Names, Washington, 1972.

CORRECTIONS

Meteorological Magazine, June 1975, p. 157, third and fourth lines from bottom of page. The equation should read:

$$\mathbf{V}_g = -\frac{1}{\rho f}\nabla p \times \boldsymbol{\kappa}$$

and in the next line the κ should be in bold type.

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